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Power Processing Units for High Powered Nuclear Electric Propulsion With MPD Thrusters

R. Frisbee, R. Das, and S. Krauthamer,
Jet Propulsion Laboratory, Pasadena CA

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Robert H. Frisbee,* Radhe S. L. Das,† and Stanley Krauthamer**

Jet Propulsion Laboratory
California Institute of Technology
Pasadena CA 91109

Abstract

This paper summarizes an evaluation of power power processing units (PPUs) for nuclear electric propulsion (NEP) vehicles using advanced magnetoplasmady namic (MPD) thrusters. The vehicle consists of three 0.5-MWe SP-1OO nuclear reactors and Rankine dynamic power conversion systems which provide a total power of 1.5 MW_e (electric). This power is used by two MPD thrusters operating at 0.75 MW_e each. The power processing units (including cabling) for this system were found to have a specific mass of 9.69 kg/kWe and an efficiency of 0.902.

I. Introduction and Background

An electric space propulsion system consists of a power source (e.g., nuclear reactor and thermal-to-electric power conversion system), a power processing unit (PPU) which converts the power source's power output (voltage) to the form required by the thrusters, and the electric thrusters. In this study, PPUS for a 1.5-MWe nuclear electric propulsion (NEP) using a dynamic power conversion system (e.g., Rankine) and high-power magnetoplasma-dynamic (MPD) thrusters are evaluated.

The two primary figures of merit for electric propulsion systems are their specific mass (α), expressed in units of kilograms per kilowatt of electric power (kg/kWe), and their efficiency (η), expressed as the ratio of power output divided by power input. This study was aimed at a detailed investigation of the mass and efficiency of PPU systems for SEP vehicles where the total "bus" power is 1.5 MW_e and the power per thruster is 0.75 MW_e (i.e., two thrusters operating at any given time).

The design of a PPU for an electric space propulsion vehicle depends on the characteristics of the power supply and the electric thrusters. This is illustrated in Fig. 1, where there is an option of a nuclear-electric power supply for a NEP vehicle, and a solar-photovoltaic power system for a solar electric propulsion (SEP) vehicle. These power supplies are then coupled to either an ion thruster or a MPD thruster.

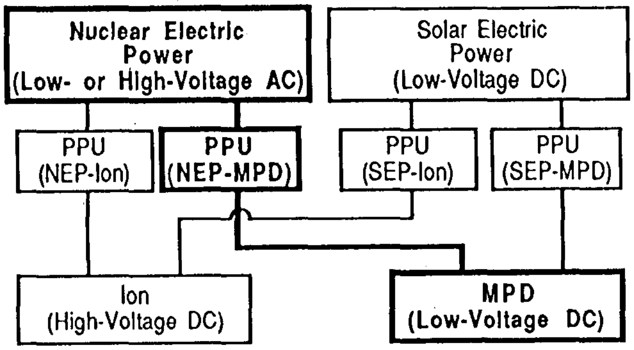

Figure 1. PPU Design Matrix

In general, a nuclear power system can have a low- to high-voltage AC output from the turboalternator of its dynamic power conversion system, whereas a solar array has a low-voltage DC power output. Similarly, a high-power ion thruster requires high voltage (ca. 2,000-6,000 V DC) for its operation and an MPD thruster requires low voltages (ea. 100 V DC). Thus, we have a PPU design matrix like the one shown in Fig. 1. In this study, we address only the NEP-MPD PPU option. The NEP-Ion,[1,2] SEP-Ion,[3] and SEP-MPD[4] PPU cases have been described elsewhere, although we shall summarize the results for the SEP-MPD PPU[4] so as to contrast and compare the differences in NEP- versus SEP-MPD PPU designs due to differences in the power systems' characteristics.

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*Technical Group Leader, Propulsion and Chemical Systems Section; Member AIAA.
†Professor and Chair, Department of Electrical Engineering, California State University at Long Beach.
**Member of the Technical Staff, Electric Power Systems Section; Member AIAA.

II. Vehicle Configuration, Power System, and Thruster Characteristics

Because the design of a PPU is a strong function of the characteristics of the vehicle design, the power supply, and the electric thrusters, we will discuss each of these next.

Vehicle Configuration. The overall vehicle configuration shown in Fig. 2 is based on an earlier study[5] of a 1.5-MWe NEP vehicle consisting of three 0.5-MW$_e$ SP- 100 nuclear reactors and Rankine dynamic power conversion systems. 'I'his vehicle was designed to transport cargo in support of a piloted expedition to Mars. The vehicle was assumed to be comprised of modules that were compatible with the Energia launch vehicle payload capability (e.g., 100 metric tons to low Earth orbit in a 5.5-m diameter by 37-m long payload envelope).

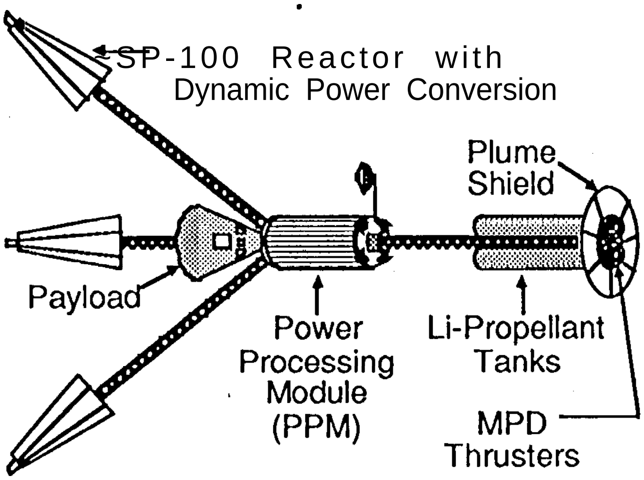

Figure 2. Megawatt-Class Nuclear Electric Propulsion (NEP) Vehicle With Li-Propellant MPD Thrusters

In the NEP vehicle, the power processing module (PPM), which contains the PPU electronics as well as the other spacecraft systems (guidance, navigation, control, telecommunications, etc.), was kept at a 24-m distance from the reactor and power conversion systems to minimize the radiation and thermal effects of the power system on the PPM. Similarly, a 25-m distance was used between the PPM and the lithium-propellant MPD thrusters in order to minimize the possibility of contamination of the PPM radiator with condensable lithium from the thruster's exhaust plume. These assumptions make it possible to package the thrusters, Li propellant tanks, deployable plume shield, and reactor-to-PPM and PPM-to-thruster cluster booms in one Energia launch, and the three reactor and power conversion modules in a second launch, Note that longer separation distances would be desirable; however, this would increase the boom wiring mass and resistive losses as discussed below.

NEP Power Source Characteristics. In terms of its impacts to PPU design, the primary differences between SEP and NEP power systems lie in their voltage output. For example, the 1.5-MWe nuclear power system has a low-voltage (ca. 100 V), low-frequency, three-phase AC output from its dynamic power conversion system (which provides constant power output during an Earth-to-Mars transit), whereas the solar array has a low-voltage (125 V) DC power output that varies with the distance of the vehicle from the sun. Thus, the output from the nuclear power system can be directly fed to a PPU rectifier for conversion to the DC voltage required by the thruster. However, the output from the solar power system must first be fed to a DC/DC converter to condition the power for the MPD thrusters.

MPD Thruster Characteristics. Both ion and magnetoplasmadynamic (MPD) thrusters are candidates for SEP and NEP vehicles. In this study, we selected Li-propellant applied-field MPD thrusters because of their projected good efficiency at low specific impulse (I_{sp}). By contrast, a self-field MPD has a lower projected efficiency and lower operating voltage than a corresponding applied-field MPD thruster.[5]

The PPU for an NEP vehicle using MPD thrusters must supply different voltages and powers to different systems in the vehicle. In general, the PPU must provide low voltages (e.g., 100 V DC) at high powers (e.g., 750 kW$_e$) for the MPD discharge, and low voltages at low powers (e.g., a total of 60 kW$_e$) for components related to operation of the MPD thruster, such as the applied-field MPD magnets (25 kW$_e$ per thruster), thruster gimbal actuators, heaters, etc., as well as for miscellaneous vehicle "housekeeping" functions.

III. Power Processor Units for SEP and NEP Systems

The primary driver in PPU design is the MPD's requirement for low voltage and high power, which results in a requirement for high-current capacity devices (e.g., 1300 to 7500 Amps). Also, the PPU must be designed to accommodate startup and shutdown transients, and be capable of isolating thruster and PPU component failures without compromising the remainder of the power or propulsion system. Thus, the PPU designs discussed below consist of both a primary high-power system and a smaller low-power power conditioning unit (PCU). For convenience, the PPU electronics components (rectifiers, filters, etc.) and switches are treated separately from the component "bus bar" wiring (both within the PPM as well as in the long booms between the PPM and the thrusters or between the PPM and the nuclear power systems).

PPU System Designs. For the NEP-MPD system discussed above, the total PPU system consists of a primary module which supplies the high-power, low-voltage DC for the thruster , and a secondary PCU module which provides the low power required by the remainder of the vehicle's systems and the thruster's components.

Block diagrams of PPUS for NEP and SEP systems are shown in Figs. 3-5. The NEP-MPD PPU consists of a multiplicity of 3-phase (3-ϕ) silicon controlled rectifiers (SCRs) or, alternatively, MOS controlled thyristors (MCTs). They receive power at 100 V AC from the turboalternators (TAs) in a dynamic nuclear power system. The SCRS are phase controlled in order to provide the variable DC voltages required to operate the MPD thrusters. High-power semiconductors are in development at the GE Corp. R&D Center and at Harris Semiconductor Corp.[6,7]

The SEP-MPD PPU receives its power at 125 V DC from the solar array. The MPD power controllers consist of a multiplicity of MCTS, diodes, and inductors. The MCTS (by their switching action) and the other associated components constitute a DC-to-DC converter and provide the required thruster current and voltage.

The switches used are non-load break type electromechanical devices that are designed to disconnect (or connect) thrusters and other components. For example, electrical power is disconnected from a thruster by first turning off the SCRS, and then by opening the non-load break thruster switch. Similarly, any of the various turboalternators or SCRS can be isolated by first driving the turboalternator voltage to zero. The TA or SCR switch can then be opened without arcing. However, the need to isolate the various components in the system does result in a complex switching topology, as illustrated in Figs. 3,4,6, and 7.

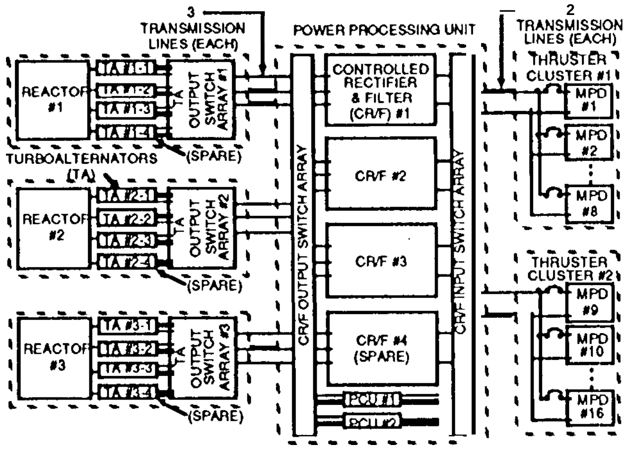

Figure 3. NEP-MPD PPU Circuit Diagram Showing Power Distribution

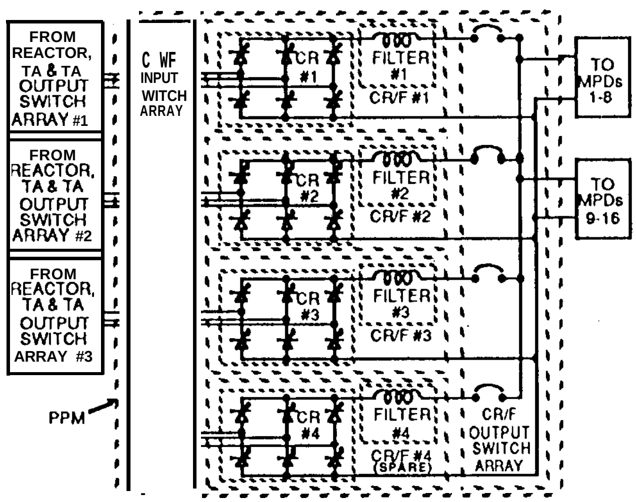

Figure 4. NEP-MPD PPU Circuit Diagram Showing Controlled Rectifier and Fiber (CR/F) Configuration

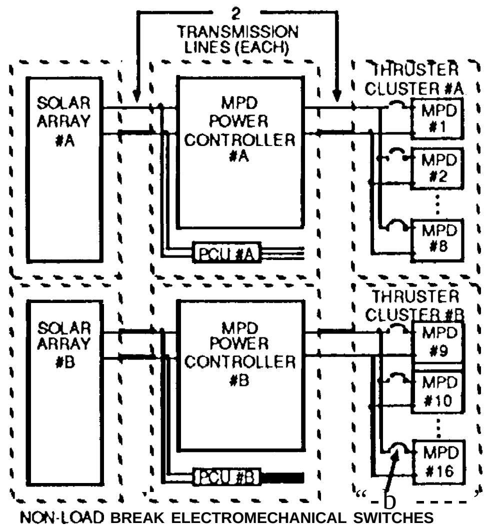

Figure 5. SEP-MPD PPU Circuit Diagram Showing Power Distribution

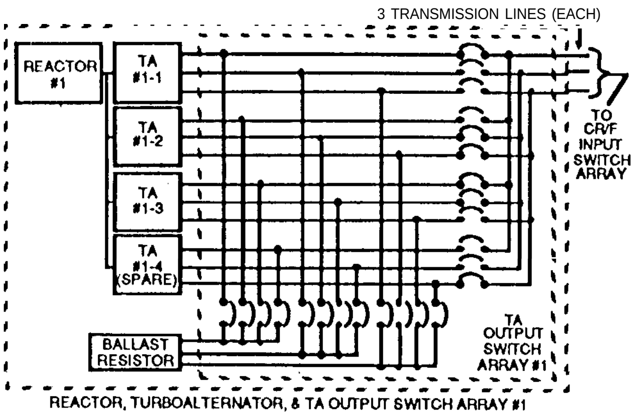

Figure 6. NEP-MPD PPU Circuit Diagram Showing Reactor Turboalternator (TA) and Ballast Resistor Switch Configuration (One of three units)

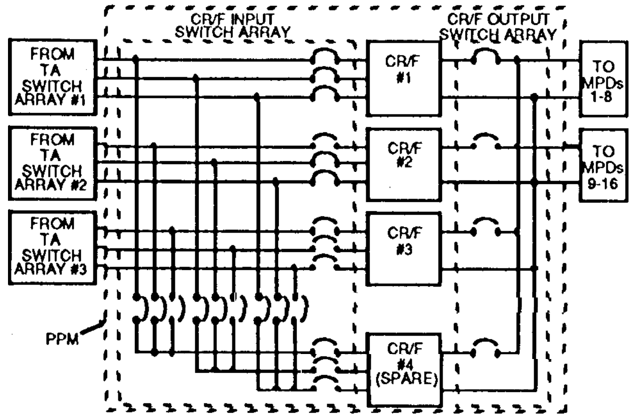

Figure 7. NEP-MPD PPU Circuit Diagram Showing Controlled Rectifier /Filter (CR/F) Input and Output Switch Configuration

Table 1 summarizes the masses and losses of the various electronics components in the PPU including all switches in the system as well as the PPM controlled rectifier/filter (CR/F) modules, waste-heat radiator (see below), and PCU. This portion of the total PPU system (less cabling) has a mass of about 3800 kg. The PPU specific mass (α_{PPU}) is defined as the ratio of PPU mass divided by the power entering the PPU; it is 2.5 kg/kW_e.

Table 1, NEP-MPD PPU PPM and Switches Mass and Power (See Table 2 for cabling.)

Item	Total No. of Units	Total Mass (kg)	Total Volume (m^3)	Total Losses (kW)	Efficiency (%)	Comments
Turboalternator (TA) Switches (100 VAC, 1333A)	36	246	0.17	1.5	99.9	Losses are for the sum of all switches
TA Ballast Switches (100 VAC, 3300A)	36	736	0.51			
CR Input Switches (100 VAC, 3300A)	21	430	0.14			
Controlled Rectifiers (CR) (100 VAC, 5000A)	4	136	0,10	40.0	97.3	25°C coolant temp.
Output Chokes (Filters, F) (100 VDC, 5000A)	4	80	0,03	3.0	99.8	25°C coolant temp.
CR/F Output Switches (100 VDC, 5000A)	4	114	0.04			
Thruster Switches (100 VDC, 7500A)	16	656	0.24			
Housekeeping PCU	2	344[a]	0.10	3.0[b]	95.0	63 kW_e in, 60 kW_e out
structure		100	0.15			
Radiator		931		(44.5)		Area = 92.2 m^2, e = 0.8
Total		3773	1.48	44.5	97.0[b]	Without PCU[b]
		(α = 2.515 kg/kW_e)		107.5[c]	92.8[c]	With PCU[c]

[a] PCU mass includes a 51,8-kg radiator for PCU waste heat of 3.0 kW.
[b] Efficiency for the high-power system only.
[c] Efficiency for the high-power system with the PCU input power counted as a loss.

PPU Redundancy Requirements. In order to achieve a low PPU specific mass, an efficient operational strategy of using a minimum number of redundant PPUS is required in which each thruster does not have a dedicated PPU. Thus, in the thruster configuration considered here,[5] there are two thruster clusters, each containing six MPD thrusters (required to provide sufficient cumulative thruster life for a two-year long Mars cargo mission),5 plus two spare thrusters for a 33-1/3 % thruster redundancy. In this study, we assumed a similar degree of redundancy for the PPU power controller modules (i.e., three operating plus one spare CR/F modules).

PPU Thermal Control. Based on the PPU electronics losses given below, the waste heat generated by the PPU electronics and switches (at 25°C) is 44.5 kW. We assumed that only the PPU electronics, switches, and magnetics would require a dedicated radiator for cooling; the housekeeping PCU mass includes its own radiator and the spacecraft cabling is assumed to possess sufficient surface area and view to space to be passively cooled. Assuming a radiator emissivity (ε) of 0.8 and mass of 5 kg/m^2, we find that the PPU electronics and switches radiator mass, when increased by an additional 5 kg/m^2 to allow for heat pipes and mass growth contingency, and a final 1 % of this total for structure, is approximately 930 kg. Other cooling options, such as active cooling with pumped fluid loops, could also be used.

PPU Cabling. The primary requirement of the PPU cabling is to transport power from the power system's turboalternators to the PPM, to interconnect the electronics components within the PPM, and to transport power from the PPM to the MPD thrusters. Because of the high DC currents encountered (e.g., as much as 7500 A at 100 V DC for the cables running to each thruster cluster), the wiring is almost three times heavier than the PPU electronics and switches. However, the cabling is also used to form the main structural elements for the reactor and thruster booms, thus partially offsetting the cabling mass penalty.

The cabling in the booms is in the form of an aluminium tube; the cross-sectional area of the metal in the tube was chosen as a compromise between minimal mass and resistive losses. Copper, aluminium, and lithium were evaluated as cable material. Interestingly, lithium has the best performance in terms of minimum resistance per unit mass, and copper the worst, However, as a structural member, lithium lacks sufficient strength, Also, because of its reactivity, lithium cable would need to be encapsulated to protect it from the atmosphere prior to launch. Thus, a "bare" aluminium cable in the form of a tube is used. (Because of the low voltages, plasma arcing in the space environment is not a problem; insulation would be needed only at points where electrical isolation is required.) A tube is used in preference to a solid rod because the tube form could be adjusted so as to provide adequate strength and surface area such that the cable is self-radiating at room temperature (-300 K).

Table 2 lists the masses and losses of cabling in the reactor booms, the PPM, and the thruster booms. Note that there is one set of three cables in each reactor-turboalternator (TA) boom, with three booms per vehicle. Similarly, there is one pair of cables in each thruster boom, with one boom per thruster cluster (TC) of 8 MPD thrusters. Finally, a 25-% mass contingency is added to the cabling mass to correspond to cross-members, insulation, etc. The total cabling mass is thus approximately 11,200 kg with 43 kW of resistive losses.

PPU Mass and Specific Mass. Tables 1 and 2 list the mass, specific mass, and losses for the PPU electronics, switches, and cabling based on a nominal input power of 1.5 MW_e for each system. However, because of losses in the various components, the actual power reaching a given system decreases as the power flows from the power source to the thrusters, as shown in Table 3. Thus, in order to calculate a "system"-level specific mass and overall efficiency that is based on the initial or "bus" power (P_o) from the power source, it is necessary to take into account the fact that the size of a given component will decrease as the power reaching it is decreased. This is illustrated in Table 4. With this correction included, the "effective" or system-level NEP-MPD PPU mass and specific mass, based on an initial or "bus" electric power of 1.5 MW_e, are approximately 14,500 kg and 9.7 kg/kWe, respectively. The corresponding values for a 1.5-MW_e SEP-MPD PPU system are 16,200 kg and 10.8 kg/kW_e.

PPU Efficiency. In determining the overall performance of an electric propulsion vehicle, the efficiencies (η) of the PPU and thruster can have a strong impact on mission trip time. This is because the total thrust is determined by the total thruster "jet" power and exhaust velocity, and jet power is given by the product of the total "bus" electric power (P_o) and the PPU and thruster efficiencies.

Table 2. NEP-MPD PPU Cabling Mass and Power

Item	No. of Assemblies	No. of Cables	Length Each (m)	Cross-Sectional Area (cm^2)	current (A)	Total Mass (kg)	Total Losses (kW)
Reactor Booms							
Turboalternator (TA)-to-TA Switch	3	12	2.2	28.3	1100	605	0.9
TA Parallel Connections	3	3	1,5	28.3	1100	103	0.2
TA-to-Ballast Resistor Switch	3	12	1.5	28.3	1100	412	0.6
Ballast Resistor Parallel Connect.	3	3	2.2	50,3	3300	269	1.2
Reactor Boom	3	3	24.0	50.3	3300	2931	12.9
Docking Connectors	3	6	0.25	50.3	3300	90	2.0
Structure (25 %)						1103	
Subtotal						5,513	17.8
(Specific Mass, Efficiency)						(3.675 kg/kW_e,	98.8%)
PPM Cabling							
Input-to-Switch-to-CR	4	3	2 . 2	50.3	3300	358	1.6
Input-to-Spare CR Switches	1	9	0.9	50.3	3300	110	0.5
Controlled Rectifier (CR) Internal	4	3	0.9	50.3	3300	147	0.6
CR-to-Filter-to-Switch-to-Output	2	4	0.5	113.1	5000	122	0.2
Output Parallel Connections	1	2	2.0	113.1	7500	122	0.6
Structure (25 %)						215	
Subtotal						1,074	3.5
(Specific Mass, Efficiency)						(0.716 kg/kW_e,	99.8 %)
Thruster Cluster (TC) Booms							
PPM-to-TC Boom	2	2	30.0	95.0	7500	3079	19.5
TC Boom	2	2	2.0	113.1	7500	244	1.1
TC Connections	2	2	2.5	139.8	7500	378	1.1
Structure (25 %)						925	
Subtotal						4,626	21.7
(Specific Mass, Efficiency)						(3.084 kg/kW_e,	98,6%)
Total Cabling and Booms						11,212	43.0
(Specific Mass, Efficiency)						(7.475 kg/kW_e,	97.1 %)

Table 3. NEP-MPD PPU Power Flow
(Includes PPU electronics, switches, and cables)

Item	TA-to-PPM Cables (2 sets)	PPU Elect.& 'Switches (1 Set)	PPM-to-Thrusters Cables (2 Sets)
Electric Power Input (kW_e)	P_0= 1 500	1482	1373
Losses ($kW_{thermal}$)			
Cables	18	3	20
Elect. & Switches		44	
Pcu (clCcl.)		59*	
P c u		$	-
Total	18		20
Electric Power Output (kW_e)	1482	1373	1353
Efficiency (%)	98.81	92.60	98.55

PCU electric power consumption is treated as a "loss" in the high-power PPU system.

Table 4, NEP-MPD PPU Total Mass, Efficiency, and Specific Mass
(Includes PPU electronics, switches, and cables)

Item	TA-to-PPM Cables (2 Sets)	PPU Electronics & Switches (1 Set)	PPM-to-Thrusters Cables (2 Sets)
Actual Specific Mass (α, kg/kW_e)	3.675	3.231	3.084
Electric Power Input (kW_e)	P_0=1 500	1482	1373
Mass (kg) = Actual α • Electric Power Input	5513	4789	4233
"Effective" Specific Mass (kg/kW_e) = Mass / P_0	3.675	3.193	2.822

In our analysis of the NEP-MPD PPU, we found that the overall PPU efficiency (η_{PPU}), including PPU electronics, cabling, and switches as discussed above, was 0.902; the corresponding value for an SEP-MPD PPU is 0.896, The major sources of inefficiencies are due to switching and conduction losses in the SCRS or MCTS, switching and magnetic losses in the housekeeping PCU, resistive (I^2R) losses in the cabling, inductors, and switches, and finally, the PCU power consumption (which is treated as a "loss" in the high-power PPU system).

IV. Conclusions and Recommendations

A power processing unit (including cabling) for a 1.5-MWe NEP vehicle using MPD thrusters was found to have a specific mass of 9.69 kg/kW_e and an efficiency of 0.902. The corresponding values for a SEP-MPD PPU is 10.78 kg/kW_e and an efficiency of 0.896.

There are a number of advanced power-control technologies that will be required to implement high-power PPUS for megawatt-class SEP and NEP vehicles using MPD thrusters. These range from relatively common near-term technologies requiring only the modest advancements in state-of-the-art, to totally new devices that must be uniquely developed for a MW-class nuclear electric propulsion PPU application. For example, electromechanical non-load break switches rated for kiloamps are available commercially, and high-power semiconductors are currently under development for terrestrial applications. However, development of radiation- and space-qualified equipment and devices (e.g., high-frequency magnetic materials and power semiconductors including power integrated circuits) will require significant improvements in technology to meet the performance assumptions made here.

V. Acknowledgements

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